Drought in the Pacific Northwest

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Management Summary

Drought is insufficient water to meet needs (Redmond, 2002). They are complex natural hazards with multiple economic, social, and ecological impacts. Historical droughts have impacted the Pacific Northwest significantly over the last few decades causing crop loss, forest mortality, limited water availability, and complex social impacts. Much research has been devoted to understanding drought including: the start and end of drought, development of a drought index to quantify severity, and understanding the impacts. In the Pacific Northwest, drought can occur when precipitation is near normal, underscoring the sensitivity to above normal temperatures.

Drought occurs in the Pacific Northwest when winters are warm or dry and mountain snowpack is meager; or when summers are hotter and drier than normal and soil moisture and streamflows are diminished. Agriculture and rangeland drought occurs on a shorter time-scale than forest or woodland drought. Furthermore, in a changing climate, droughts are projected to occur more frequently, in part due to warmer winters and warmer and drier summers (Dalton et al. 2013).

The Bureau of Land Management (BLM) commonly uses the Palmer Drought Severity Index, or PDSI, (Palmer, 1965) as its drought metric of choice for many purposes. PDSI was the first complex drought metric that was developed, and has been used in many official Federal and State management plans. However, the index has significant flaws that limit its efficacy, particularly in mountainous regions (NDMC, 2012). The BLM does not have a policy that specifies the use of a single preferred metric, and instead managers are encouraged to use a range of indicators and variables (B. Boyd, personal communication, 2015).

We advise that BLM adopt the use of a relatively new multi-scalar index called the Standardized Precipitation Evapotranspiration Index (SPEI), which considers both precipitation and potential evapotranspiration (PET) (Vincente-Serrano et al. 2010). It performed well over the Northwest in a recent study by Abatzoglou et al. (2014), and works for rangeland (3-6 month) and forest (24-48 month) drought, and is useful for climate change considerations as it is sensitive to temperature through the PET component. With climate change, drought is projected to become more frequent due to increased

temperatures and evapotranspiration. This index can be used in tandem with other climate indices and data, including best professional judgment of land managers.

A number of tools are readily available for drought tracking and early warning, but these applications vary in their capacity and function. One such tool, the US Drought Monitor, is used for Federal funding dispersal in times of drought, but functions well as a high-level drought indicator. We have evaluated the tools and recommend two for use by the BLM. The West Wide Drought Tracker is hosted by the Western Regional Climate Center and tracks SPEI at the 4km scale on a near-real time basis. The tool uses high-quality gridded input temperature data for the Pacific Northwest, and also calculates PDSI (single value) for BLM NIFC Predictive Services Areas used in wildland fire management. The Pacific Northwest Drought Monitoring System from the University of Washington calculates soil moisture conditions and adds value to the information contained in the SPEI index, particularly for rangeland drought considerations.

Tool locations:
US Drought Monitor
http://droughtmonitor.unl.edu
West Wide Drought tracker
http://www.wrcc.dri.edu/wwdt/
UW Drought Monitor for the Pacific Northwest
http://www.hydro.washington.edu/forecast/monitor_west/

Introduction

Drought is a complex, slow-moving natural hazard with extensive economic and ecological consequences. Formulating a uniform proper definition of drought is difficult, and has eluded both scientists and managers. The American Meteorological Society (1997) divides drought definitions into four distinct categories (meteorological, hydrological, agricultural, and socioeconomic). More info about these drought types can be found at http://drought.unl.edu/DroughtBasics/TypesofDrought.aspx. This breakdown is useful as a first-pass when considering a formal definition for drought, but mixes both the causes and its impacts while still remaining fairly limited in its scope. Alfieri (2007) cautions against

considering no one category on its own as they are all inextricably connected. Perhaps the most fitting definition is the one proposed by Redmond (2002). Drought is "insufficient water to meet needs." This definition is fairly simple on its face, but Heim (2002) notes that drought is an imbalance between supply and demand, and the Redmond definition addresses both. The research on drought is extensive, and this report discusses the highlights as it pertains to the Bureau of Land Management (BLM).

The goal of this report is to provide the BLM with an appropriate spatial subdivision of the Pacific Northwest (defined here as Oregon and Washington) as it relates to drought, an index for managing wildland drought in both rangeland and forests, and advice on monitoring the onset of drought. This report also describes future projections of drought conditions in the Pacific Northwest.

Climate of the Pacific Northwest

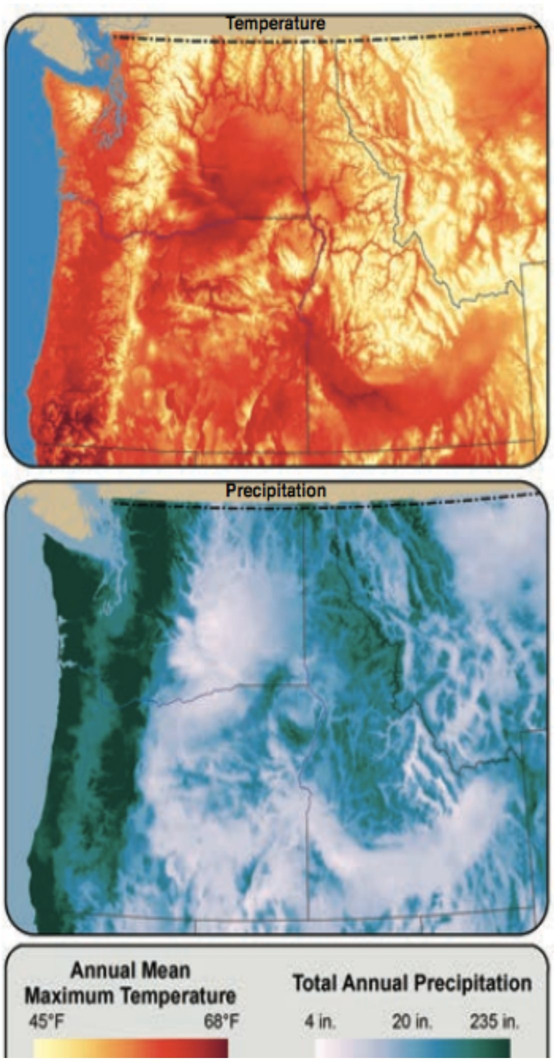

Figure 1. Annual mean maximum temperature and precipitation for the Pacific Northwest from Dalton et al. 2013

Despite its cool and wet winters, the Pacific Northwest is drought prone and has experienced significant drought in the recent past Both geography and general atmospheric circulation ensure that precipitation is not distributed equally across space and time in the region. The annual cycle of precipitation is such that most of it falls between the months of October to May, punctuated by a warm and dry summer that lasts well into September. The majority of the precipitation falls in the western portion of the region, with the Cascade Mountains creating a significant rain shadow between the wet west and the arid east. Some smaller mountain ranges

such as the Olympics, Oregon Coast Range, and Blue/Wallowas topographically enhance precipitation in localized areas (figure 1). Temperatures are relatively homogenous across the region; the Pacific Ocean acts to moderate temperatures. The coolest temperatures occur in the higher elevations and along the coast, but the maritime influence keeps the west side warmer in the winter than the east side. The largest diurnal temperature range is east of the Cascades, where the maritime influence is not as prevalent.

Due to the seasonal cycle of precipitation, the region relies heavily on a system of reservoirs for summertime water supply, especially in the more arid parts of the region. The most significant reservoir in the region is not manmade. Rather, the most important reservoir is the mountain snowpack that typically accumulates during the cool season. The region relies on a robust mountain snowpack to melt out and recharge soil water and streams in the warm and dry summer months. The snow in the Pacific Northwest is historically particularly sensitive to temperature, in part due to the proximity to the Pacific Ocean. Much of the low elevation snow falls at a temperature at or near freezing. The Pacific Northwest is always on the precipice of a meteorological drought due to the spatial and temporal characteristics of precipitation, but also because of the sensitivity to the mountain snowpack to temperature. Hot temperatures also play a role in depriving soil of its moisture, and the Pacific Northwest has experienced hot and dry summers in the recent past. The summers of 2013 and 2014 were both warmer and drier than the historical average in the Pacific Northwest. On the demand side, there are many competing uses: hydropower, agriculture, recreation, instream flow for fish, and many more. For land managers, sufficient water supply is necessary for habitat and plant growth in forests and rangelands. The length and timing of the growing season can impact plant demand for water from the soil. In warmer years, plants rely on this soil moisture earlier than usual. Summer remains the most relevant climatological season for fires; hot summer temperatures can deplete soil moisture rapidly and fire season in the Pacific Northwest extends into the late summer (Hessl et al. 2004).

Historical Droughts

While droughts can fall into one or all of the AMS categories, we know they all start because of a lack of water. This lack of water stems from a lack of precipitation or above average

temperatures (drought caused or exacerbated by policy or management of water resources is beyond the scope of this study). Bumbaco and Mote (2010) classified flavors of recent Pacific Northwest drought and all began with some sort of anomalous climate conditions such as warm and dry winters or warm and dry summers. Multiple flavors of drought can exist in one water year, for instance, a warm winter may be followed by a warm and dry summer.

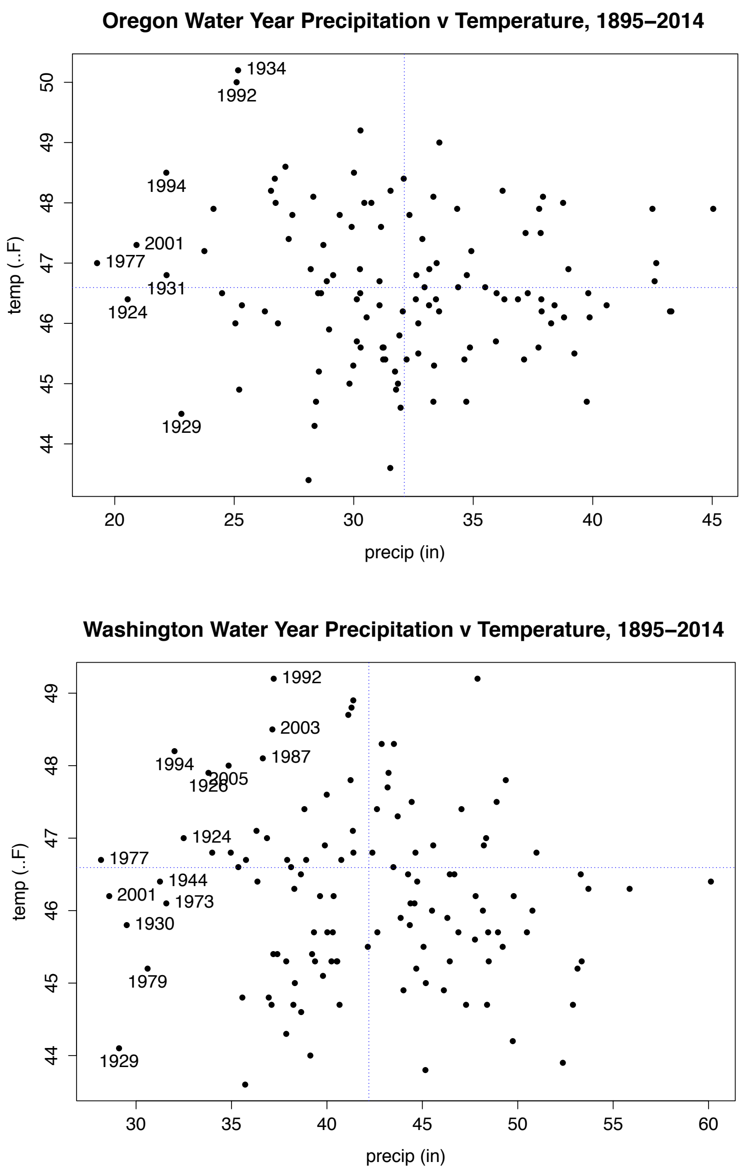

Figure 2. (a) Oregon and (b) Washington Water Year (October 1 – September 30) Precipitation v Temperature for the observational period (1895-2014). Key years are noted. Blue dotted lines represent mean temperature and precipitation.

Examining the annual precipitation pattern in the instrumental period (1895-present) for Washington and Oregon reveals that annual precipitation itself is highly variable. Some of the driest years on record coincide with significant drought years (e.g., the 1930s/Dust Bowl, 1977, 1992, 2001). Yet, relying only on precipitation to identify drought is insufficient for the snowpack-dependent Pacific Northwest as it does not necessarily capture evolving drought. Winter 2014-2015 received near-normal precipitation in the Pacific Northwest, but snowpack was at near record lows. Drought conditions are developed in summer 2015, especially in eastern Oregon and Washington (personal communication, state climate offices of Washington and Oregon, 2015).

AghaKouchak et al. (2014) used both temperature and precipitation in calculating drought in California, which also relies on snowpack for warm season water supply, noting the significant interdependence of temperature and precipitation in defining drought in snowpack-dependent areas. Plotting water year precipitation against temperature may identify years that were anomalously warm, anomalously dry, or both and can tease out more of the nuances of drought in the Pacific Northwest. In Oregon, this captures 1934 and 1992 as very warm and also dry. The blockbuster droughts of 1977 and 2001 were very dry, but temperatures were near normal. The 1977 drought, largely considered the drought of record in the Western US, was an absolute outlier in terms of winter precipitation in both Oregon and Washington (figure 2).

Drought conditions are not caused by one particular synoptic pattern in the atmosphere – dry winters can be the result of significant ridging from high pressure, such as in 2013-2014, or perpetual southerly flow coupled with elevated air temperatures in 2014-2015.The 2003 drought, which was the end of a four year turn of the century drought in the PNW was exacerbated by intense summertime temperatures in the PNW.

Drought in the Pacific Northwest can affect only a portion of the region. The 1992 drought occurred because of a hot and dry summer following a winter with low snowpack. It rendered Malheur Lake almost completely dry (Ivey et al. 1998). The 1992 drought had its reach in the urban water utility sectors as well. Water shortages in the city of Seattle

occurred because the city spilled water from its reservoir to comply with flood control rules, and there was limited snowmelt to recharge supply (USGCRP, 2001). In southern Oregon, 2001 was a major drought year that began as the result of low winter precipitation. The impacts were substantial: deliveries were not made to Klamath Project irrigators in order to honor the water rights of the tribes and fish species listed under the Endangered Species Act. 2005 was primarily a Washington drought, and low winter snowpack led to a statewide drought declaration.

At the writing of this report, 2015 developed into an agricultural and hydrologic drought, with near-record low snowpack remains in Oregon and Washington and persistent higher than average temperatures. Similar to 1977, snowpack was abnormally low, but precipitation is near normal. Climate change models show that the winter of 2015 looks like the winters of the future: warm, and a little wetter (see page 16) The low-elevation snow in the Pacific Northwest is particularly sensitive to temperature as it is already ‘warm’ snow (Nolin and Daly 2005).

Drought Indices

Given the ecological, social and economic costs of drought, much energy and focus has been placed on developing a ‘silver bullet’ drought index that addresses both the onset and severity of drought. A desire to quantify drought into one number or ranking is understandable and desirable for management purposes; managers are often challenged with managing for multiple purposes. As a result, a number of different drought metrics and indices have been developed over the last 50 years, each with inherent strengths and weaknesses. The very first of these indexes, the Palmer (1965) was sophisticated for its time, and was a calculation of drought using a water balance equation. Other commonly used drought indices include subsequent modifications of the Palmer (1965) (Palmer Z, PDSI, self-calibrated PDSI) index as well as the Standard Precipitation Index (SPI) or percent of normal precipitation.

There are a number of papers, studies, and information sheets available that discuss the general pros and cons of these indices (Hayes 2006, NIDIS 2015). Drought index “bake-offs” have existed through time (Keyantash and Dracup, 2002). For instance, Guttman (1999)

advocated for the SPI (McKee, 1993) over the Palmer (1965). As is often the case, these indices prove their value or show their flaws in hindsight after much of the drought has occurred. Reducing complex hazards to a single number remains attractive, which is why researchers consistently strive for a new index that fully captures the severity and impact of drought. They have been adopted into numerous State and Federal drought management plans, often with little explanation as to why they were used or chosen over a similar metric and sometimes have a significant role.

BLM does not desire a suite of metrics or indices, but rather advice on one or two solid indices useful for representing drought in rangeland and forests. The literature varies on the appropriate time scale for each, but generally agricultural (or rangeland) drought is short term (3-6 months) due to the importance of soil moisture. Forest drought emerges at longer time scales, though short-term drought may exacerbate wildfire and contribute to forest mortality (personal communication, H. Lintz). In this work, we explore how well certain indices (Table 1) serve the BLM in their intended purpose. We use a first cut approach from two recent papers exploring drought in the Pacific Northwest. Abatzoglou et al. (2014) tested drought indices against unregulated streamflow, one of most basic drought indicators. Bumbaco and Mote (2010)'s typology of drought stresses the significance of temperature in PNW drought.

Standard Precipitation Index

The importance of soil moisture in agricultural drought, particularly east of the Cascades, requires that the index have some sort of evapotranspiration component. Therefore, indices that do not use temperature or evapotranspiration in their calculation such as the SPI (McKee, 1993) or percent of normal precipitation will not be considered despite their relative simplicity. The SPI also assumes that the precipitation data are normally distributed, which is not often the case with short-term climate data (Agnew, 2000). The SPI would work if the cause of drought was merely a lack of precipitation in the Pacific Northwest. The lack of an evapotranspiration component in SPI meant that it failed to capture adequately the 2012-2015 drought in eastern Oregon.

Palmer Drought Severity Index

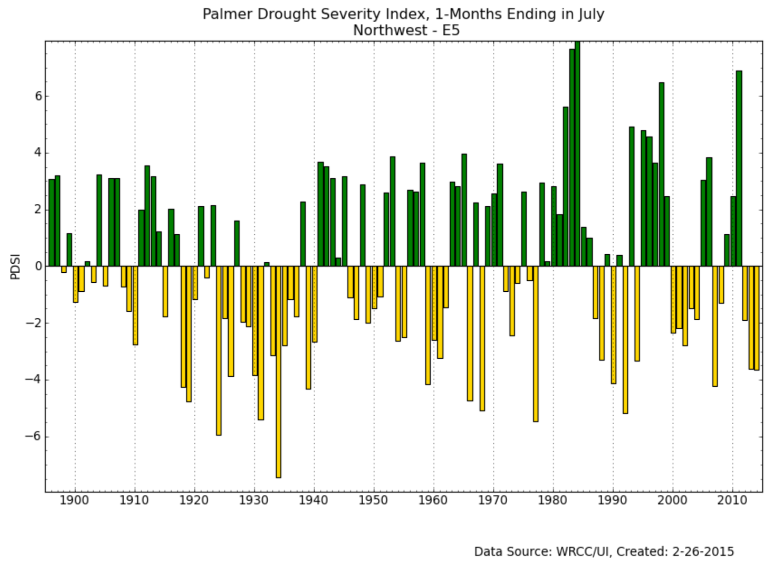

Figure 3. Palmer Drought Severity Index (PDSI) for 1-months ending in July for southeastern Oregon

The BLM typically uses the Palmer Drought Severity Index (PDSI) because of its familiarity and longevity. The PDSI was developed around the water balance equation, getting at the desired supply and demand side of the drought equation. The PDSI considers temperature in its calculation, which is important for drought in the Pacific Northwest. However, it does not necessarily perform well in mountainous regions and does not distinguish well between rain and snowfall (Abatzoglou et al. 2014). It was first calculated using data from the Midwest, and the values which officially range from -4.0 (extreme drought) to +4.0 (extremely moist) were chosen without scientific significance. As it is only calculated on the 1-month time scale, it is not a multi-scalar index, limiting its use (NDMC 2012). Values lower than -2.0 are arbitrarily defined to signify moderate drought or worse, but for example, in southeast Oregon alone (figure 4) alone this occurs often, and does not necessarily reflect whether or not a drought occurred. Additionally, the values can exceed -4 and +4, and the instances which exceed these values are not given an additional designation. For instance, extreme drought can occur at -4 and -6. The PDSI does capture historical extreme drought years due to the severity in the climatological anomalies (e.g., 1934, 1977, 1992), but it is generally unreliable for operational purposes as it does not capture the onset of drought very well with a singular time scale (Hayes, Alvord, Lowrey 2007).

Standardized Precipitation Evaporation Index

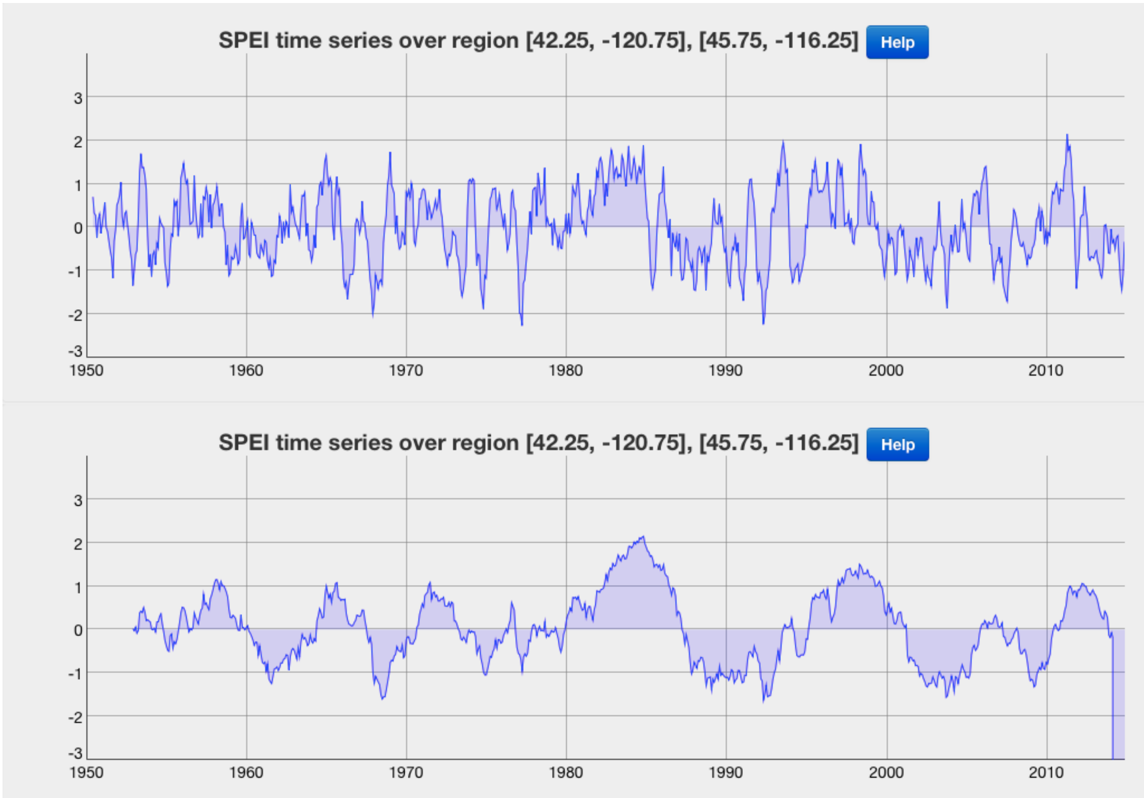

Figure 4. SPEI at 6 month and 36 month time scales for eastern Oregon and Washington

The Standardized Precipitation Evaporation Index (SPEI) developed by Vincente-Serrano et al. (2010) is a relatively new index that is gaining traction in the climate and drought community because it is a multi-scalar index, similar to SPI. Unlike SPI, it incorporates potential evapotranspiration into its calculation. It captures the effect of temperature on water demand (Vincente-Serrano et al. 2010), which is important for the Pacific Northwest and for exploring future drought potential in climate change analyses. Abatzoglou et al. (2014) found that the metric generally had higher predictive power than the PDSI in the Pacific Northwest, and that using a gridded temperature data set (such as PRISM) adds value over using single station NOAA climate data. PRISM incorporates other networks such as SNOTEL into its observations, adding richness into the data. As the SPEI is statistically-based, it is based on local climatological information and lends itself well to climate change considerations (Vincente-Serrano et al. 2010).

Recommendations:

Drought Index

We advise that BLM shift away from the use of the PDSI and adopt SPEI as its metric of choice. SPEI as a metric is more robust because it is calculated on multiple timescales, making it dual-purpose for both forests and rangelands. SPEI at 3-6 month is more appropriate for situations where in-season dry conditions are most impactful; scales from 1-3 years are more appropriate for long-term drought.

Subdividing Region

The wildland fire community currently uses PSAs to assess conditions and allocate resources in areas with similar wildfire behavior. NOAA's climate divisions are also candidates for subdividing the state. We recommend that BLM use existing PSAs to subdivide the region because they are a familiar boundary, and furthermore, SPEI is already calculated in near-real time for PSAs. While the largest droughts often have a fingerprint across the entire two-state region, it is appropriate to consider drought at these scales for resource management even though the boundary may be arbitrary as it is geo-political or management-based and not explicitly created for drought or climate monitoring purposes.

Drought Monitoring

There are many online drought tools and products already created and updated in near-real time. These products range in their ease of use and relevance for the PNW, so we offer advice to the most robust, relevant, and useful for BLM's needs. OCCRI works extensively with the Oregon Water Resources Department in considering drought development and declaration. We have tested the use of some of these applications over time in drought, particularly in the 2013-2015 drought.

United States Drought Monitor

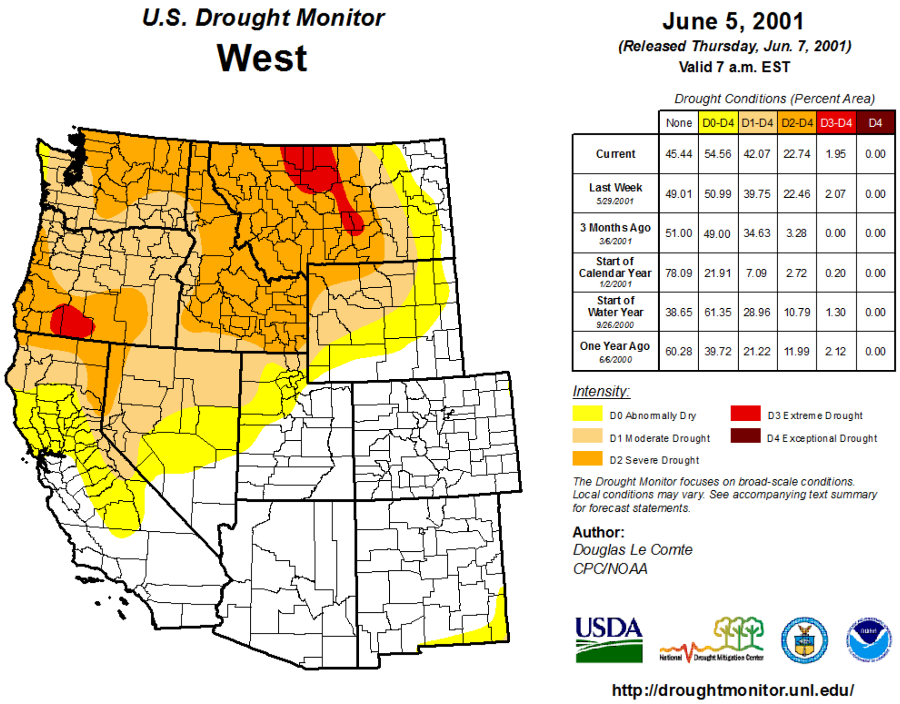

Figure 5. US Drought Monitor for the Western US on June 5, 2001 (http://droughtmonitor.unl.edu)

The United States Drought Monitor (USDM, or Drought Monitor) is a spatially-depicted drought index that is updated weekly and frequently overlooked because of its facial simplicity. The monitor consists of five categories ranging from abnormally dry (D0) to exceptional drought (D4). The monitor is a bit of a science and an art (personal communication, Kelly Redmond), relying on data and climate experts coupled with on-the-ground local knowledge and impacts. US Department of Agriculture uses the Drought Monitor for drought disaster funding dispersal. It is easy to communicate to non-specialists, produced weekly, and generally captures drought development well. The Pacific Northwest drought of 2001 was captured in the early days of the drought monitor, and captured the greater severity of the Klamath Basin, where economic, social, and ecological impacts were substantial (Figure 5). The largest droughts in the past 15 years are prominent on the US Drought Monitor, including the drought of 2003 in Oregon. Ground-truthing the data and indices with best expert judgment is an advantage and disadvantage of the USDM. The regional and local expertise judgment means that it carries less weight as a scientifically-

derived index. The expert judgment varies over time, and there is no real evaluation of the experts. The period of record is relatively short, so it cannot be used for historical comparisons. The USDM categories start with “abnormally dry” though we know Pacific Northwest drought can happen when precipitation conditions are near normal, but winter temperatures are above normal (personal communication, US Drought Monitor List Serv, 2009-2014). It is a useful tool for monitoring evolving drought, and a good tool for a high-level ‘first pass’ to determine whether a region is or is not in drought. Many drought indices, including SPEI, are incorporated in the US Drought Monitor.

Given the infrequency of meteorological stations in some of the lesser-populated areas in the Pacific Northwest, and the finding from Abatzoglou et al. (2014) that using a gridded dataset made for a more robust result, some sort of spatially-distributed tool is preferred to a station-by-station index. The West Wide Drought Tracker (WWDT) hosted at the Western Regional Climate Center provides a near-real time update (monthly) of temperature and precipitation percentiles at a 4km spatial resolution using PRISM (Daly et al.). The WWDT also calculates SPEI for each BLM PSA at a monthly time step. While managers may prefer only one index, but we recommend a two-pronged backstop approach for drought monitoring and suggest BLM utilize a drought monitoring system in addition to SPEI: the near-real time Drought Monitor from the University of Washington.

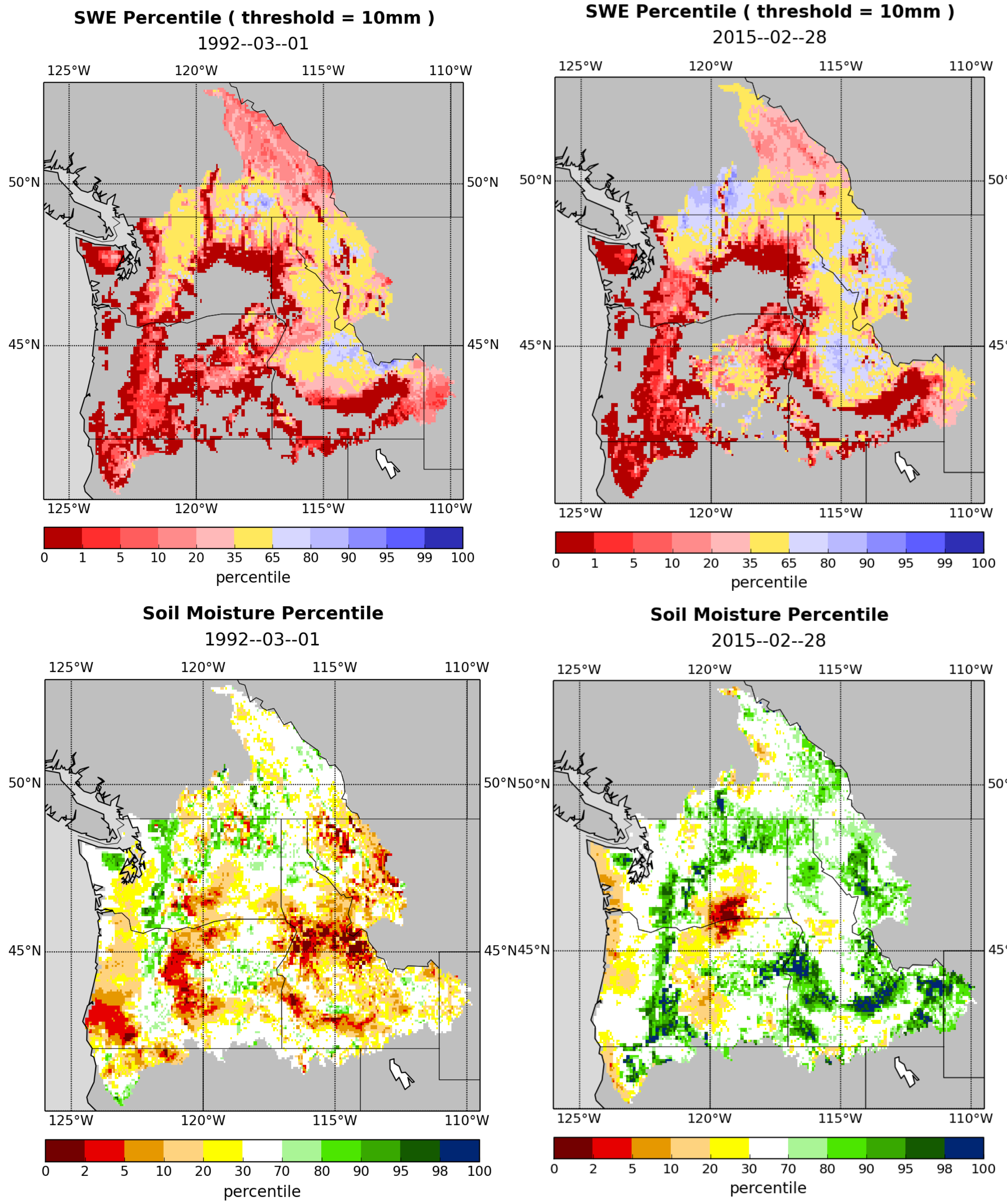

Figure 6. A comparison of snow water equivalent (SWE) and soil moisture from the UW Drought Monitoring System between the end of winter 1992 and 2015.

The University of Washington Pacific Northwest Drought Monitor has been operational since 2013 and is a value-added product for their needs. It calculates daily soil moisture, runoff, and snow water equivalent (SWE) based on the Variable Infiltration Capacity (VIC) model, which uses observed daily temperature and precipitation. The monitor is

experimental, but reproduces historical drought conditions well. For instance, the 1992 drought looked similar to 2015 in regards to SWE on March 1, 1992, but soil moisture was at a much lower percentile in the 1992 drought (Figure 6). The soil moisture tracking is at the HUC scale, on the daily time step, and aggregated over the water year.

Future Projections of Drought

Drought is projected to become more common in the future in western North America largely from rising temperatures and evapotranspiration (Maloney et al., 2014; Cook et al., 2014). In fact, the winter warmth of 2014-15 is a preview of what average conditions are projected to be in the Northwest by the middle of the century (Figure 7).

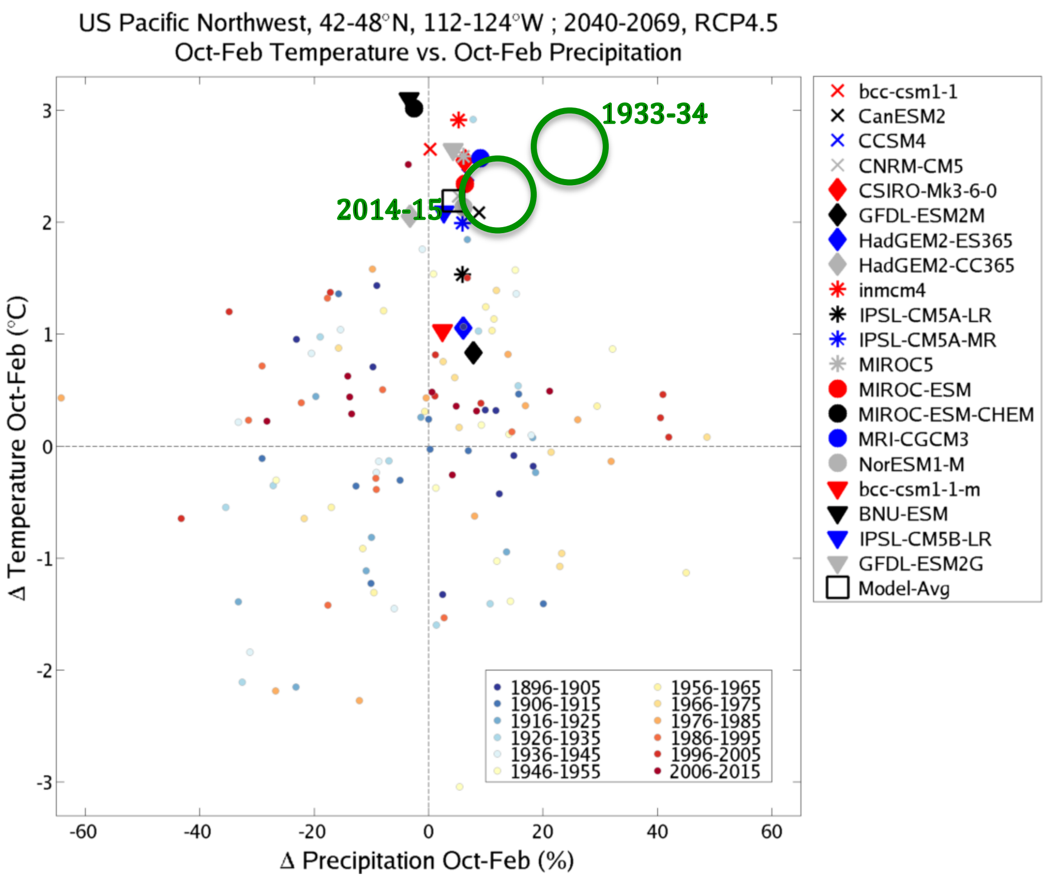

Figure 8. Projected changes in winter (Oct-Feb) precipitation and temperature for the Northwest from 20 different climate models for the 2040-2069 period relative to the 1971-2000 average for a future pathway with some level of climate policy (RCP4.5). Smaller dots show observations from 1896-2015 color coded by decades. Winters of 1933-34 and 2014-15 are noted (Abatzoglou, with permission, unpublished).

Average annual temperature in the PNW is projected to increase by 2-8.5°F (depending on the future emission scenario) by mid-century with greater warming in the summer. There is little divergence between RCPs 4.5 and 8.5 (assumes more greater greenhouse gas emissions than 4.5) through mid-century. Inland areas, less moderated by the Pacific Ocean, are projected to experience relatively greater warming. Annual precipitation in the PNW is projected to increase slightly by mid-century, though some models project decreases. Summer is projected to receive less rainfall in the future, while other seasons receive more (on the model average) (Dalton et al., 2013). Even though the cool season may receive more rainfall in the future, warmer temperatures will cause a greater proportion of that precipitation to fall as rain rather than snow, limiting the build up of seasonal snowpack particularly during the peak snow season in Jan-Apr (Maloney at al., 2014). In addition, projected rainfall increases in western North America contribute more to increased evapotranspiration than to runoff having implications for water availability despite increases in precipitation (Maloney et al., 2014). Model projections also show a strong decrease in soil moisture largely due to increasing evaporation (Dai, 2013).

Several studies have analyzed future drought characteristics for various drought indices for western North America comparing the SPEI with the SPI (e.g., Touma et al., 2014) and PDSI (e.g., Cook et al., 2014; Vicente-Serrano et al., 2014). Minimal change in length of droughts is projected for both SPI and SPEI (Touma et al., 2014). Because the climate of western North America is so variable, future drought occurrences never shifted permanently outside the range of current variability (Touma et al., 2014).

Using the SPI, decreases in annual precipitation in western North America (WNA) lead to greater drought occurrence (a few more 6-month D4 events per 45 years), but not greater spatial extent or duration (Touma et al., 2014). However, the Northwest is projected to experience slight increases in precipitation. Being based only on precipitation, using the SPI under climate change will lead to a severe underestimation of future drought risk in the Pacific Northwest. The SPEI shows stronger increases in spatial extent (+30% in WNA), duration, and occurrence (15 to 50 more events per 45 years in the latter half of the century) than SPI and other indices and shows greater model agreement (Touma et al., 2014). Even though models agree on sign of change, there is still a large range in the magnitude of projected change (Touma et al., 2014).

Future PDSI and SPEI both indicate robust drying across multiple models. The SPEI tends to put a greater percent of land area in drought conditions than the PDSI (Cook et al., 2014) because of its higher sensitivity to PET changes. Future increases in precipitation in mid to northern latitudes are offset by increases in potential evapotranspiration until about 50°N where the zonal-average PDSI and SPEI values are positive (less drought) by the end of the century (Cook et al., 2014).

The SPEI is more sensitive than PDSI to changes in potential evapotranspiration (Cook et al., 2014; Vicente-Serrano et al., 2014). Increased PET intensifies drying in areas that are already dry, but can also increase drought conditions in areas projected to experience little drying or even increased precipitation. This effect is particularly strong in western North America (Cook et al., 2014). The PDSI is less sensitive to changes in evapotranspiration making is less suitable as a drought index in areas in which ET changes are most relevant (Vicente-Serrano et al., 2014). The SPEI on the other hand, being highly sensitive to ET changes is appropriate for PNW droughts. Since the SPEI is more sensitive to ET in arid regions and more sensitive to precipitation in humid regions, it works as a "perfect supply and demand system" (Vicente-Serrano et al., 2014), it is the most suitable index for the entire NW which experiences a wide range of climates.

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